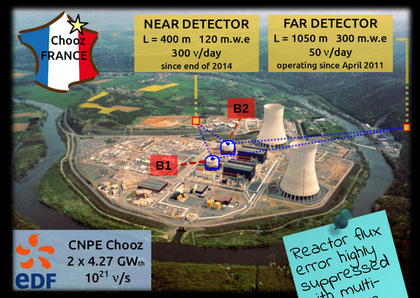
First Double Chooz θ_{13} measurement via Total neutron Capture detection

D. Navas-Nicolás[1], A. Oralbaev[2], P. Soldin[3] on behalf of the Double Chooz Collaboration

[1]Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France (navas@lal.in2p3.fr), [2]NRC Kurchatov Institute, Moscow, Russia (oralbaev_ay@nrcki.ru),
[3]RWTH Aachen University, Aachen, Germany (soldin@physik.rwth-aachen.de)

H. De Kerret *et al.* Nat. Phys. **16**, 558-564 (2020)
https://rdcu.be/b3FE4

The Double Chooz Experiment

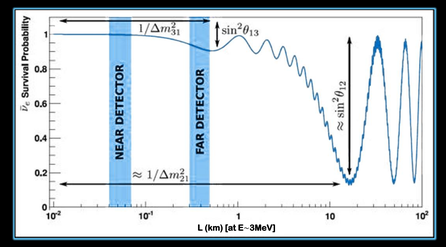


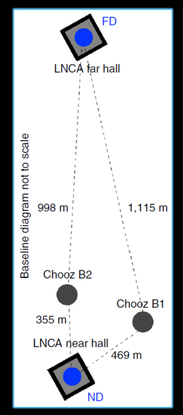
Reactor flux error highly suppressed with multi-detectors

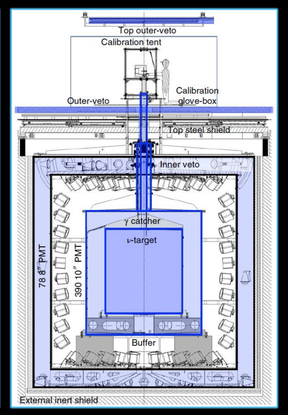
In reactor experiments, the determination of the θ_{13} **mixing angle** is extracted via the survival probability of $\bar{\nu}_e$:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

$\bar{\nu}_e$ survival probability







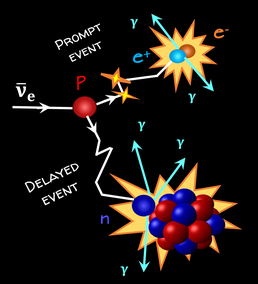
Multi-detector analysis

- 455 days FD (no ND)
- 363 days FD } FD and ND taking
- 258 days ND } data simultaneously

Total neutron Capture (TnC)

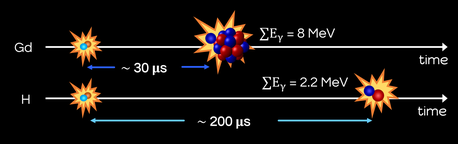
$\bar{\nu}_e$ are detected via the **inverse β decay** (IBD)

$$\bar{\nu}_e + p \to e^+ + n$$



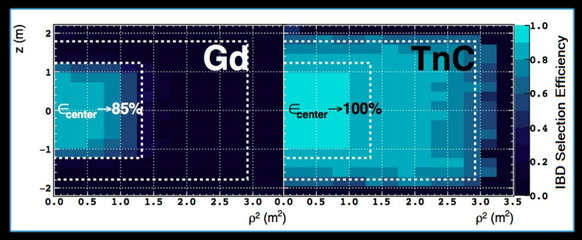
$\bar{\nu}_e$ interacts with a proton of the organic scitillation

- **Prompt signal:** energy losses + e^+ anihilation
  E(vis)≃ E($\bar{\nu}_e$) - 0.8 MeV
- **Delayed signal:** neutron capture on **Gadolinium** (Gd) or **Hydrogen** (H)



Rate (day^{-1})	FD	ND
IBD Candidates	112	816
BG Breakdown		
Accidental	4.13 ± 0.02	3.110 ± 0.004
Fast Neutron	2.50 ± 0.05	20.85 ± 0.31
^{9}Li isotope	2.62 ± 0.27	14.52 ± 1.48
Stopped μ	<0.19 @ 98% CL	<0.21 @ 98% CL
Others (^{12}B, Bi-Po)	< 0.01	0.04 ± 0.01
Total		
∑ exclusive	9.3 ± 0.3	38.5 ± 1.5
2 reactors off (17 d)	9.8 ± 0.9	39.6 ± 2.5
Signal to BG	11.0	20.0

Small Gd-target (8.3 t) Gd+H+C-target (~30 t)



Major increase of the detection volume

Increase of signal statistics by more than a factor of 2.5

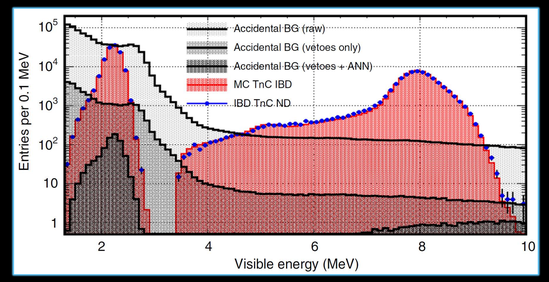
The IBD space-time coincidence relies on a multivariable ANN

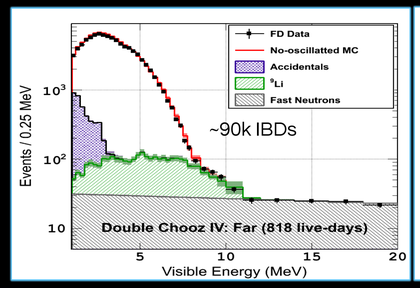
IBD acceptance criteria widely opened to **integrate over all nuclear capture**: H, C and Gd

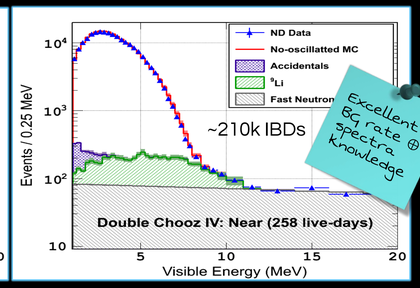
Accidental BG rejected >4 orders of magnitude with ANN

Excellent data-to-MC agreement

The energy-scale uncertainty has negligible impact (<0.05%)







Excellent BG rate & spectra knowledge

θ_{13} Oscillation Fit Results

Rate + Shape Fit

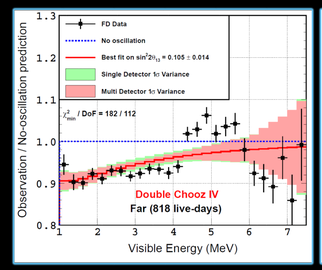
Simultaneous comparison of FD and ND observed IBD rate + shape data to non-oscillated flux predictions

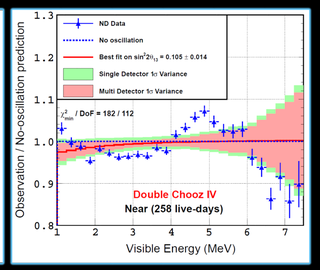
$$\chi^2 = \sum_{ij}(N_i^{obs} - N_i^{exp}) M^{-1}_{cov} (N_j^{obs} - N_j^{exp})^T + \text{Penalty pulls + Reactor off}$$

$$N_i^{exp} = N_i^{MC}(\theta_{13} = 0, \epsilon_{det}, a', b', c') \sum_{E_\nu}\left[1 - \sin^2(2\theta_{13})\sin^2\left(\frac{1.267\,\Delta m^2_{ee}[eV^2]\,L_\nu[m]}{E_\nu[MeV]}\right)\right] + N_i^{BG}$$

New θ_{13} value released in T. J. C. Bezerra Neutrino2020 presentation

$$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$$





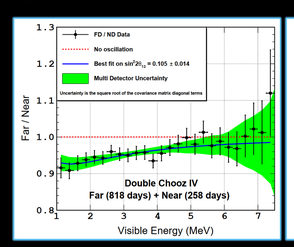
Parameter	Uncertainty	Fractional
Reactor flux	0.0081	7.6%
Detection	0.0073	6.8%
Energy	0.0018	1.7%
Background	0.0018	1.7%
Δm^2_{ee}	0.0018	1.7%
Statistics	0.0054	5.0%
Total	0.0141	13.3%

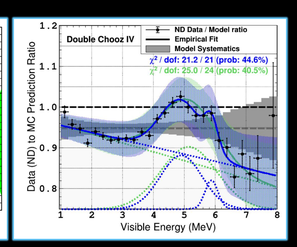
Reactor systematics (FD-I with no ND)

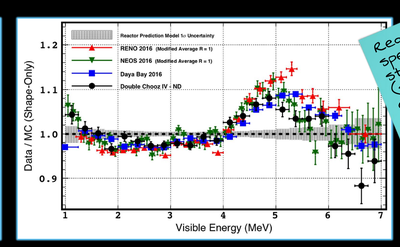
Detection systematics (poor proton# GC)

Effective correlation uncertainty = 0.0065

Spectral distortion





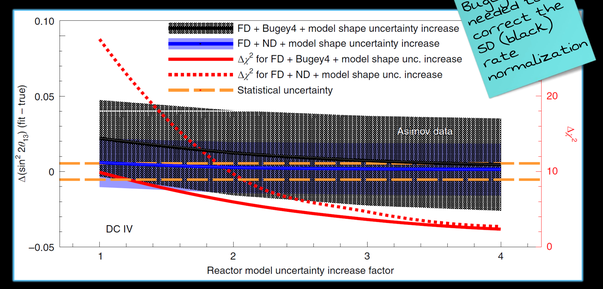


Reactor spectral structure (shape only) overall agreement

- Distortion effect out of the oscillation range. Interdetector ratio demonstrates the suppression of the 5MeV spectral distortion
- Excess events in 4 – 6 MeV region in agreement with flux model
- Empirical fit: negative slope and single or double peak

Impact of reactor model on θ_{13}

Bugey4 is needed to correct the SD (black) rate normalization

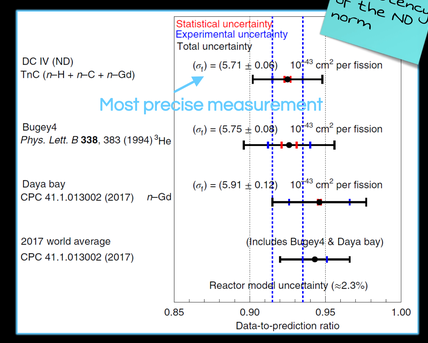


- **Stability of the θ_{13} measurement** scrutinized and demonstrated against the behaviour of the reactor model for both the SD and MD configurations
- An **increase of a factor greater than 3 of the uncertainty of the reference spectrum** causes both a more robust θ_{13} value (<1% effect) and alleviation of the χ^2 tension

Mean Cross-section Per Fission $\langle\sigma_f\rangle$

$$\langle\sigma_f\rangle = \frac{N(\bar{\nu}_e)}{N_p \epsilon}\left(\sum_{r=B1,B2}\frac{\langle P_{th}\rangle_r}{4\pi L_r^2 \langle E_f\rangle_r}\right)^{-1}$$

Check the consistency of the ND norm



- Provides a measure of the total reactor neutrino integrated flux per reactor